Strain-Hardness Correlation in Aluminium Butt Cold Welded Joints

D. Iordachescu[1], M. Iordachescu[2], J. Planas[2], J.L. Ocana[1] and M. Blasco[1]

[1] Centro Láser-UPM, Universidad Politécnica de Madrid, Ctra. de Valencia, km. 7,3; Campus Sur U.P.M. (Edificio "La Arboleda"), 28031 Madrid, Spain
[2] ETSI Caminos, Canales y Puertos, Dep. Ciencia de Materiales, Universidad Politécnica de Madrid, c/ Profesor Aranguren s/n, 28040 Madrid, Spain

E-mail: danut.iordachescu@upm.es

Abstract

Butt cold welding is a solid phase welding process where welding occurs by plastic deformation of the metals to be welded. It is obtained by cold pressing until the expansion of the contact zone of the two parts creates contaminant-free areas, allowing the contact and creation of a common lattice between the opposing clean surfaces. Consequently, butt cold pressure welding raises interesting theoretical and practical issues related to the material large plastic deformation, and its consequent hardening. The method used to determine the 99.5%Al hardness-strain correlation is based on Vickers micro-hardness HV0.5 test results on upset bars at different values of effective strain. Two approximations of the relationship between hardness and the effective strain were determined, namely as a rational function, and as a power function. These functions were used for validating an original FEM model of 99.5% Al bar butt cold welding.

Introduction

Since components produced by cold pressure welding include spacecraft and automotive parts, bimetal products and household items, understanding the mechanisms and the details of the process is of significant industrial importance due to the structures weight reduction and fuel consumption decreasing.

Butt cold welding is a solid-phase welding process where welding occurs by plastic deformation of the metals to be weld. It is obtained by cold pressing when the two parts contact surfaces expansion creates contaminant free areas, allowing the contact and creation of a common lattice between the opposing clean surfaces [1-3].

It has been reported that cold welding of metals is affected by various parameters such as the amount of deformation [2-5], the metal under consideration, the temperature of welding [3], the amount of upsetting pressure, the time of welding [1], the metal purity [1], the lattice structure [1], the surface preparation [2, 5-6], the geometry of deformation zone (shape factor) and the post-heat treatment of welds [1].

Consequently, butt cold pressure welding raises interesting theoretical and practical issues related to the material large plastic deformation, and its consequent hardening [5]. The paper investigates the strain-hardness correlation during 99.5% Aluminium bars butt cold welding. The analytical description of the 99.5% Aluminium strain-stress variation vs. hardness, and the related hardness experiments, are validating the process simulation and FEA results.

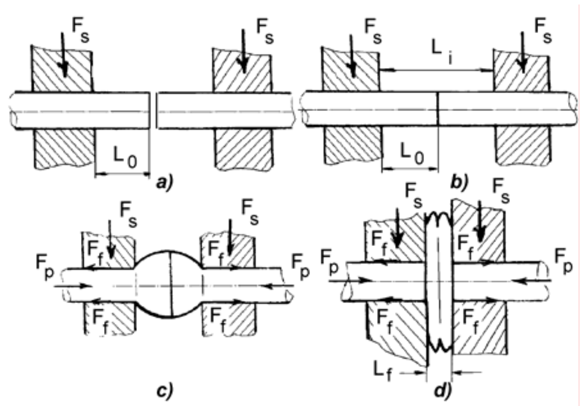

Figure 1: Butt cold welding phases: a) – initial clamping; b) – bars in contact before upsetting; c) - upsetting phase; d) – welded joint after upsetting; F_s – clamping (squeezing) force; L_0 – one bar initial standoff; L_i – total initial standoff; F_p – upsetting force; F_f – friction force; L_f - final standoff (after upsetting)

Experimental procedure

Figure 1 presents the main stages of the butt cold welding process. After the initial squeezing of the bars in the clamping devices with the force F_s (Figure 1,a), the bars are brought in contact (Figure 1,b) and the upsetting may start. An important parameter of this initial phase is the initial standoff of each bar [3], L_0, and the total initial standoff, L_i, respectively (usually, $L_i = 2\ L_0$). The pressing force F_p is used during the upsetting phase (Figure 1,c), generating the bars end deformation by the desired level (Figure 1,d). The final total standoff L_f is another important parameter. During upsetting, the friction force F_f that appears at the contact of the bars with the clamps helps avoiding bars sliding.

To determine the material hardening produced by up-setting, different butt cold welding tests were performed using 99.5% Aluminium bars of 10 mm diameter.

Material stress-strain curve

The effective stress-strain curve of 99.5%Al was obtained by means of low speed compression tests carried out at room temperature on cylindrical specimens with height-to-diameter ratio of h/d = 1, using a Teflon lubricating foil to ensure homogeneous deformation. The results are well approximated by the following 3rd order polynomial equation:

$$\sigma = 6.14\cdot 10^{7} + 1.6\cdot 10^{8}\cdot\varepsilon - 8.62\cdot 10^{7}\cdot\varepsilon^{2} + 1.57\cdot 10^{7}\cdot\varepsilon^{3} \quad \text{[Pa]} \qquad (1)$$

Hardness vs. effective strain; f(ε)=HV characteristic curve

The method used to determine the 99.5%Al hardness-deformation dependency is based on Vickers microhardness HV0.5 tests results on upset bars (until the cold weld is achieved) of different known values of effective strain. Figure 2 shows the measurements results. Moreover, to avoid problems of inhomogeneity, the hardness measurements were made around the center of each contact/weld area of the pressed bars [7].

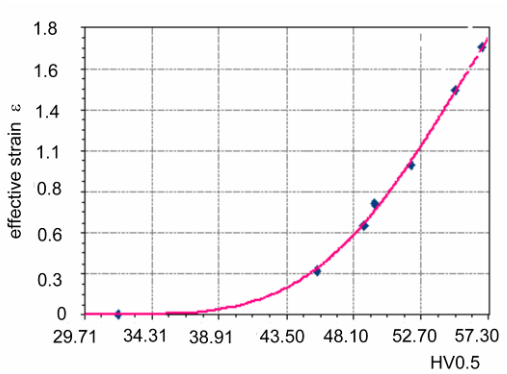

Figure 2: Vickers microhardness HV0.5 dependency on effective strain ε, in case of cold pressing 99.5% Al bars, up to cold welding achievement

Under these circumstances, two approximations of the relationship between hardness and effective strain were determined: firstly, as a rational function (2), the secondary, as a power function (3).

The rational function form is:

$$HV = \frac{32 + 332.08\cdot\varepsilon}{1 + 6.47\cdot\varepsilon - 0.41\cdot\varepsilon^{2}}, \qquad (2)$$

The power function which describes the effective strain-hardness dependency is:

$$HV = 51.87\cdot(\varepsilon + 0.02)^{0.122}, \qquad (3)$$

These effective strains – hardness approximations are bijective functions, each of them allowing the inverse functions definition on the entire domain of bars upsetting, cold welding, respectively. Thus, the inverse functions, *f(HV)=ε,* approximations are described by:

$$\varepsilon = 4.33\cdot 10^{-3}\cdot e^{0.15HV} \qquad (4)$$

or

$$\varepsilon = e^{97.94 - \frac{1329.92}{HV} - 18.31\cdot \ln(HV)} \qquad (5)$$

Hardness vs. effective stress; f(HV) = σ

The set of equations from above are usefull for the analitical description of hardness – stresses dependency. Thus, a convenient system is described by:

$$\begin{aligned} &\sigma = 6.14\cdot 10^{7} + 1.6\cdot 10^{8}\cdot\varepsilon - 8.62\cdot 10^{7}\cdot\varepsilon^{2} \\ &\quad + 1.57\cdot 10^{7}\cdot\varepsilon^{3} \\ &\varepsilon = 4.33\cdot 10^{-3}\cdot e^{0.15\cdot HV} \end{aligned} \qquad (6)$$

where the first equation is the 3rd degree polynomial regression of the experimentally determined strain-stress curve of 99.5%Al (1) and the second one is the effective strain - hardness equation (4).

After solving the system of equations (6), the function which characterizes the effective stresses-hardness dependency is:

$$\sigma = 6.14\cdot 10^{7} + 6.94\cdot 10^{4}\cdot e^{0.148\cdot HV} - 16.23\cdot e^{0.296\cdot HV} + 1.28\cdot 10^{-3}\cdot e^{0.444\cdot HV} \qquad (7)$$

This can be useful for predicting the material effective stresses when the hardness values are experimentally determined. Moreover comparative analysis of predicted FEA resultant stresses and the correspondent analytically obtained values (HV dependent) might be achieved.

The equations (1-7) are valid for effective strains domain of [0, 2], in case of low speed compression tests carried out at room temperature on 99.5% Al.

Material hardness tests results

The material hardness was studied on aluminium bar samples at deformations, δ, of 0.35, 0.5 and 0.75 (when a qualitative cold weld forms), by performing Vickers microhardness measurements HV0.5, according to ISO 6507/2 (due to symmetry reasons, only a quarter of the welded/pressed bars was used into the microhardness imprints sketch). Comments on hardness measurements, on 20 mm bar length, in case of 99.5%Al bars butt cold welding (δ=0.75) are presented together with the FEA predicted ones, in the chapter 4 of the current work.

FEA results on bars butt cold welding process

Iordachescu M. et al. [3], previously demonstrated that a good quality cold butt weld may be usually achieved by assuming the bars minimum deformation, δ, of 0.75.

The FEM model of the butt cold welding based on process/deformation control by displacement gives information about the material deformation, strain-stress couple, and consequent hardening, etc. Thus, to adapt to the material large deformations, which occurs during the butt cold welding process, the material different description was used: for the linear-elastic part through Young modulus and Poisson ratio and for the plastic part through the effective stress-strain curve, described by equation (1).

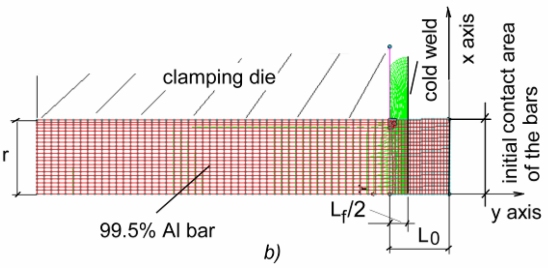

Figure 3: FEM of butt cold welding, initial and final phase of cold weld formation corresponding to the bar deformation δ = 0.75; L_0 – initial standoff; $L_{f/2}$ – final standoff

The code COSMOS/M2.5 was used for FEM modelling the process. Two identical 99.5%Al bars, 10 mm diameter, 35 mm length, were considered to be butt welded. Therefore, according to Figure 3, the process model geometric symmetry has allowed that only a quarter of the joint to be modelled. The clamping dies are considered as being rigid, with sticking friction acting to prevent bars sliding. The main part of the FEM mesh contains 4-node Plane2D axis-symmetric pressure displacement elements. Near the die corner, where the material rollover occurs, the elements have triangular shape, accommodating the deformation mode. Gap elements are used to model the adherent contact between the bar and the clamping die during pressing. Finally, the following constraints were applied: isothermal deformation, non-linear static analysis, elastoplastic material model, large strain and large deflection, and prescribed displacements. Newton–Raphson iterative method is used to ensure at any time step the convergence of the stiffness matrix.

According to the FEM analysis results the material flow and hardening that occurs during the cold welding process of the bars are discussed below.

Material induced stresses and its consequent hardening

The material flow due to the bars process of pressing, and consequently after the cold welds formation, results also into the material hardening and stresses increasing (Figure 4).

The pressed material flowing outward the clamping area, the barrel shape forming at cold welding, respectively is well illustrated in Figure 4a. The inside flowing of the material, and its consequent hardening is shown in Figure 4b, through B1-B5 equivalent Von Mises profiles. Thus, the higher stresses are registered at B1 line, where the cold welding occurs. The stresses values decrease from the weld/contact area to values of $6.4 \cdot 10^7$ Pa, the plastic domain starting point, in case of 99.5%Al. Moreover, the plotted equivalent Von Mises stresses on B1-B5 lines (Figure 4b) follows the material inside flow previously demonstrated by the authors [5].

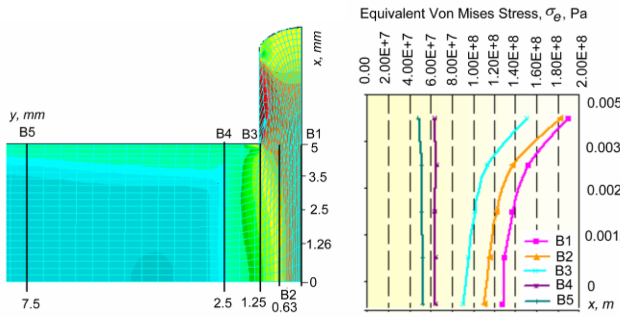

Figure 4: a) Von Mises stress FEA results and B1-B5 lines position; b) B1-B5 Von Mises equivalent stresses (material deformation, δ = 0.75)

Strain-Hardness Correlation

FEM validation through hardness analysis

The FEM of 99.5% Al bar butt cold welding validation was based on comparing the hardness measurements values with the predicted ones resulted from introducing into the equation (2) the correspondent values of the FEA effective strains.

Moreover, according to Figure 5a, the hardness values on different points from A1-A4 lines can be further predicted through FEA corresponding strains results. Thus, Figure 5b,c,d resulted, by comparing the predicted hardness values with the measured ones and the base metal hardness average. The shape of the predicted/measured hardness values on the pressed bars radial direction illustrates the inside flow of the material and its consequent hardening. Thus, highest values of 55 HV0.5 are registered into the weld area. Here, the commercial cold-hardened 99.5%Al hardness, (HV0.5 = 47), is surpassed. At 5 mm from the weld, the hardness values are still surpassing the base metal hardness, of 28 HV0.5, being almost constant on the bar radius. These results demonstrate the existence of the intermediate zone, previously described as being The Mechanically Affected Zone.

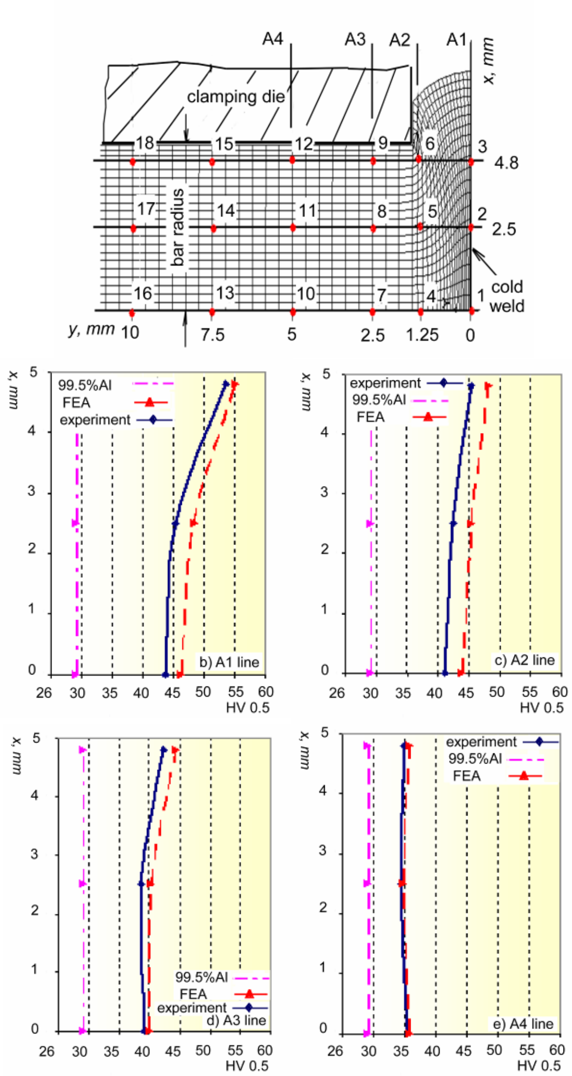

Figure 5: Microhardness variation (FEA predicted and measured) on the bar radial direction, in case of 99.5%Al bars butt cold welding (δ=0.75) a) Microhardness imprints sketch; b) Microhardness variation A1 line; c) Microhardness variation A2 line; d) Microhardness variation A3 line; e) Microhardness variation A4 line

The error, E, between the FEA results and the measurements was computed with:

$$E = \frac{HV_{FEA} - HV_{tests}}{HV_{tests}} 100 \ [\%] \quad (8)$$

where HV_{FEA} are the computed values of the material hardness using the FEA predicted strains results on B1-B4 lines (Figure 6b) and HV_{tests} are the measured hardness values, in case of butt cold welding achievement, of δ = 0.75, respectively.

The error average of 4% demonstrates the model viability, and its potential usage for predicting also dissimilar bars butt cold welding.

Stresses and hardness conformity

As Figure 6 illustrate, during the upsetting process, at bars butt cold welding, the effective strain increase is accompanied by the material hardening and stresses increasing, respectively.

In case of bars butt cold welding process, similar shapes of curves presenting the stresses – strains and hardness – strains dependencies, Figure 6a,b, attest the stresses vs. hardness conformity. The hardness – strains diagram was plotted for the both measured and FEA predicted cases.

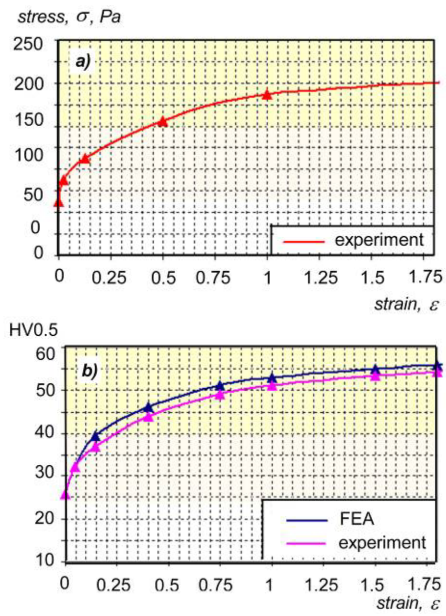

Figure 6: Stresses-strains and hardness-strains conformity: a) effective stresses – effective strains dependency in case of 99.5%Al; b) hardness – effective strains curves, measured and FEA predicted

Conclusions

The paper brings original contributions, which are presented together with several conclusions, as follow:

- ✓ An original polynomial regression of third degree equation was found to describe the material effective stress-strain curve, used for 99.5% aluminium bars butt cold welding FEM-based analysis.

- ✓ The FEA results for butt cold welding show the compatibility of the predicted material flow and its consequent hardening with the tests results.

- ✓ Hardness vs. effective strain equation, obtained by processing the measurements results, was necessary for FEM model validation; the average error between the model and measurements calculus was about 4%, demonstrating its viability and potential usage, with adequate changes of materials description, for predicting the materials properties in case of dissimilar bars butt cold welding.

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